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CITATION:

Kobayashi, Hirohide ...[et al]. j.Pod units as a sustainable building system. SANSAI : An Environmental Journal for the Global Community 2006, 1: 61-75

ISSUE DATE:

2006-01

URL:

http://hdl.handle.net/2433/108258

j.Pod units as a sustainable building system

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Abstract: The j.Pod unit is a new type of timber building system that uses a semi-monocoque structure composed of mainly timber rib-frames and several steel connectors. Semi-monocoque structures operate on a similar principle to the single-shell construction of aircraft and boat designs, and are self-supporting or structurally independent. This means j.Pod units are light but extremely strong and rigid with sufficient resistance against earthquake load. They can also be combined in many different ways as required. The j.Pod unit is ideally suited for use in cellular type buildings such as houses, apartments and hotels. By lengthening the units' dimensions, they may also be manipulated for application in larger building projects.

The unit consists of simple components that may be easily manufactured and assembled. By constructing the unit primarily from domestic timber – in particular, Japanese cedar, much of which is not being used efficiently in the Japanese timber market – the developers of the j.Pod concept hope to revitalize Japan's domestic timber industry. Finally, the unit is expected to re-establish local networks among builders, users and timber resources that have been lost in recent years owing to an increasing dependence on the use of cheaper imported timber, the logging and transportation of which has been at great environmental cost.

Keywords: sustainability, environment, building system, timber structure, timber industry.

1. Introduction

A culture of unique timber structures developed in Japan, supported by an abundance of timber resources. However, over the course of modernization, a great many structures have been built across most of the country using manufactured materials such as concrete and steel. Concerns have been raised recently with regard to the environmental impact of these modern buildings. In contrast, it is argued that the characteristics of wooden structures have a comparatively low impact on the environment. From the standpoint of sustainable environment, it would appear that a much more central role should be allocated to timber structures in terms of national building priorities. In order for improvements to take place in the future, we have to overcome not only technical issues but also a number of urban- and forestry- related social issues concerned with timber. The authors are presently involved in the co-development of the j-Pod unit as a "sustainable building system" – a unit that may be applied in both detached housing and mid-rise buildings. This paper presents the challenge of an alternative architecture for sustainability.

2. Social issues on domestic timber concerns

2.1 Forestry timber concerns

The Japanese have lived with many kinds of natural disasters over their country's long history. Yearly typhoons are just one of the well-known types of natural disaster. The damage inflicted by typhoons has become increasingly serious in recent years – sometimes triggering typhoon-floods. The photograph in Figure 1 shows an increasingly common occurrence whereby timber has become stuck under a bridge and caused a massive typhoon-flood. Cases such as this arise when planted trees from supposedly maintained forests are felled by wind or landslide or left unused in logging areas, only to slide into and eventually block the flow of a river in the event of heavy rains. The problem is mostly the result of poor forest management: planted timber requires daily maintenance in order for it to be used effectively and safely. Typhoon floods triggered by drift-wood that has dammed rivers are a typical case where the impact of a natural disaster is exacerbated by human error.

The Japanese timber industry has been in decline in recent years, while the amount of timber used in the country has increased by 80 million m^3 per year. For seven years, Japan's self-sufficiency ratio in gross timber materials and lumber has been settled at 18 per cent and 30 per cent respectively (see the report by Japan Housing and Wood Technology Center 2004). This situation has been affected by the decreased demand for timber products and manufacture, as well as the lower cost of imported timber.

Fig. 1 Timber lodged under a bridge in Saijo city, 2004 (Source: Saijo city)

Fig. 2 A street of timber houses that collapsed in the Great Hanshin Earthquake (Source: AIJ)

In the positive use of domestic timber resources, the developers of the j.Pod unit concept seek to stimulate Japan's timber industry and promote the recovery of the forest environment. This should help to mitigate the impact of natural disasters. The widespread use of small-sections of single modular lumber in constructing the rib-frame structure on which the j.Pod unit is based will make it easier to use currently unused timber resources, notably Japanese cedar, which is grown widely in the country.

2.2 Urban timber concerns

The Great Hanshin Earthquake in January 1995 seriously affected the urban areas closest to its epicenter. More than 5,000 human lives were lost, mainly as a result of collapsing buildings (Architectural Institute of Japan 1996) (Figure 2), many of which were timber structures. The data shown in Table 1, which lists suffocation and burns as the primary cause of death for casualties in the earthquake (Hyogo Medical Association 1996), indicates that earthquake safety should be made the top priority in attempts towards disaster mitigation. Many of the casualties of earthquake-related fire were found to have died in collapsed wooden houses. Electrical fires were triggered when the houses fell down and the fires spread through the exposed timbers. Fallen beams blocked the streets, preventing escape or fire fighting and fuelling the fires. Clearly, earthquake safety measures to ensure that buildings do not collapse are a crucial factor not only in keeping buildings standing but in preventing fires.

Cause of death	Number of people
Crushing death/ asphyxia	4,224 (78%)
Burn death/ Burn injury	504 (9%)
Head and neck injury	282 (5%)
Visceral injury	98 (2%)
Traumatic shock	68 (1%)
Others	188 (3%)
Unknown	124 (2%)
Total	5,488

Table 1 Cause of casualties in the Great Hanshin Earthquake

The 1995 earthquake influenced the public against timber structures as people reevaluated the vulnerability of such buildings. However, many houses built with a conventional timber frame – as well as many of those incorporating modern timber structures developed in recent years by housing companies – withstood the earthquake's tremors. It was found that conventional timber houses built before 1981 suffered from particular damage on account of their age and the lack of safety specifications in place at the time they were built. Recent amendments to the Building Code in 2000, which focuses today on performance based regulations (defining regulatory principles, required performances and their technical criteria) rather than on specification based regulation (defining specifications such as product names, standards of building materials, etc.) have widely expanded the possibilities for technological development in relation to timber buildings. The j.Pod unit is secured by a performance-based analyzing method known as the "dynamic analysis method", which estimates structural timber safety using the resulting data from the strength tests of rib-frames. This method can be used to demonstrate timber's antiseismic potential to people. Moreover, assembled units are both light-weight and strong. These two qualities contribute to the unit's earthquake-proof capacity and sustainability against other natural disasters.

2.3 Timber concerns and the building industry

The disaster vulnerability of timber houses mentioned above led people to reject timber constructions, especially in the postwar years of spectacular economic growth and accelerating urbanization. Figure 3 shows how the supply of timber houses has declined yearly in recent decades.

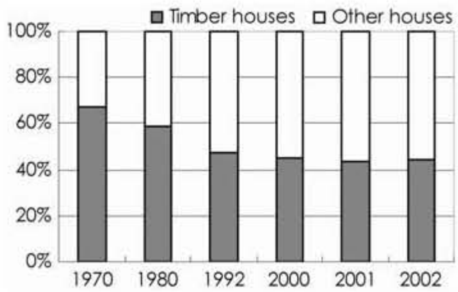

Fig. 3 Rate of construction of new timber houses

Previously, many houses and apartment buildings had been constructed using timber. In 1970, new constructions using timber structures accounted for 67.4 per cent of the total number; however, this number had dropped to 44.2 per cent by 2002 (National Land and Transportation Ministry 2004). A combination of social issues and a decline in demand for these structures converged with the aging and decrease in the number of skilled carpenters. In the meantime, many of the current generation of carpenters, who can no longer be called skilled carpenters, work predominantly with the factory precut wood favored by a rationalized building industry, using laminated lumber and standardized construction methods. Most rationalized housing types built with prefabricated or steel structures have developed under the conditions of economic growth and urbanism since the 1960s.

The j.Pod unit emerges as one response to the present situation. It promotes simple methods of manufacture, transport, land use and construction to produce a cost-effective, low-energy and quality building.

3. Development of the timber semi-monocoque system

3.1 The j.Pod concept

A reevaluation of the role played by timber is valid not only from the viewpoint of the social issues explored above, but also from a global environmental perspective. Maintained forests grown by reproductive and sustainable methods through appropriate forest management help prevent global warming by fixing or sequestering atmospheric carbon in the period of tree-growth and continuing to store it after the conversion from timber to lumber. In addition, timber material consumes comparatively less energy than steel and concrete materials at the time of manufacturing, processing and dismantling. Moreover, the use of local materials for local consumption can reduce the amount of energy used for their transportation.

The j.Pod unit was developed to address local and global issues. The concept of the unit centers on its timber structure, which combines earthquake-proof safety, a simple construction method, and the positive use of domestic timber material. Figure 4 shows how the use of not only domestically but locally grown timber is recycling-oriented. It encourages the growth of local industries linking forests and cities on one hand, and stimulates regional development and disaster mitigation through self- and local-support mechanisms on the other. The localization represented by these regional networks becomes a vital part of the process by which global environmental issues can be tackled at the local level (Kobayashi, Kito et al. 2005). The possibilities and strengths arising from these interconnections between forest and city are encapsulated in the name "j.Pod", which expresses how "pods" or units are "jointed" together in a structural system.

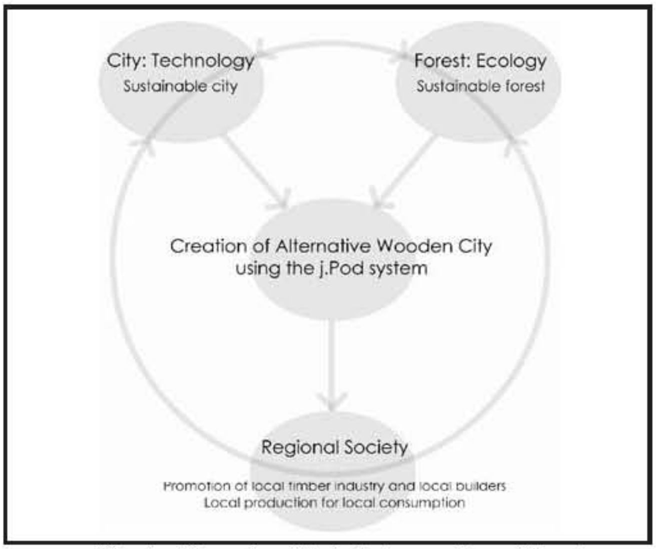

Fig. 4 The regional links between city and forest

3.2 Outline of the j.Pod unit

Semi-monocoque structure

The j.Pod unit uses a semi-monocoque structure composed of mainly rib-framed timbers and several steel connecters (Figure 5). A monocoque is a structure in which all loads are carried by the skin. In a semi-monocoque structure, the loads are shared between the skin and a framework that provides local reinforcement for openings, mountings, etc. The j.Pod unit is based on a kind of semi-monocoque structure, containing timber rib-frames held in place by steel angles and stiffened by structural plywood panels. The plywood can be replaced by other suitable skins or by steel cross-bracings (Figure 6).

Vertical loads, such as gravity or floor weight capacity, are carried by the framework and transmitted to the steel corner angles. Lateral loads, such as earthquake or wind, are carried by the framework along the width-direction of the unit's façade and by cladding panels or cross-bracings in its depth direction, where they are also transmitted to the steel corner angles. Units are joined together at each end of the steel angles (Figure 7).

This structural principle secures the structural independence of the unit, which can be assembled in many different combinations, stacked high and linked freely. By

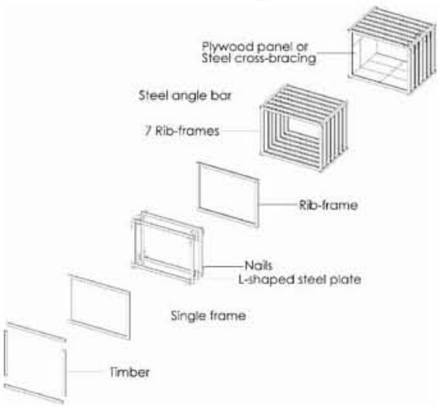

Fig. 5 Components of a unit

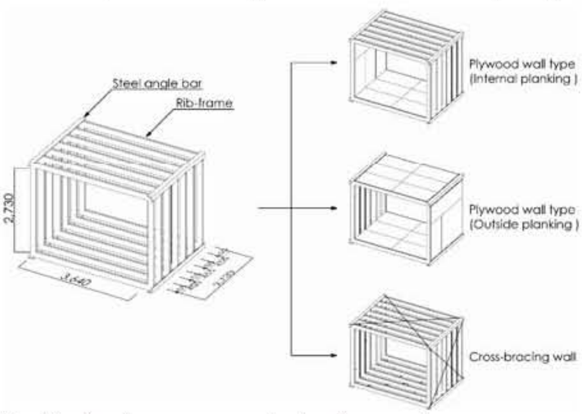

Fig. 6 Semi-monocoque structural concept

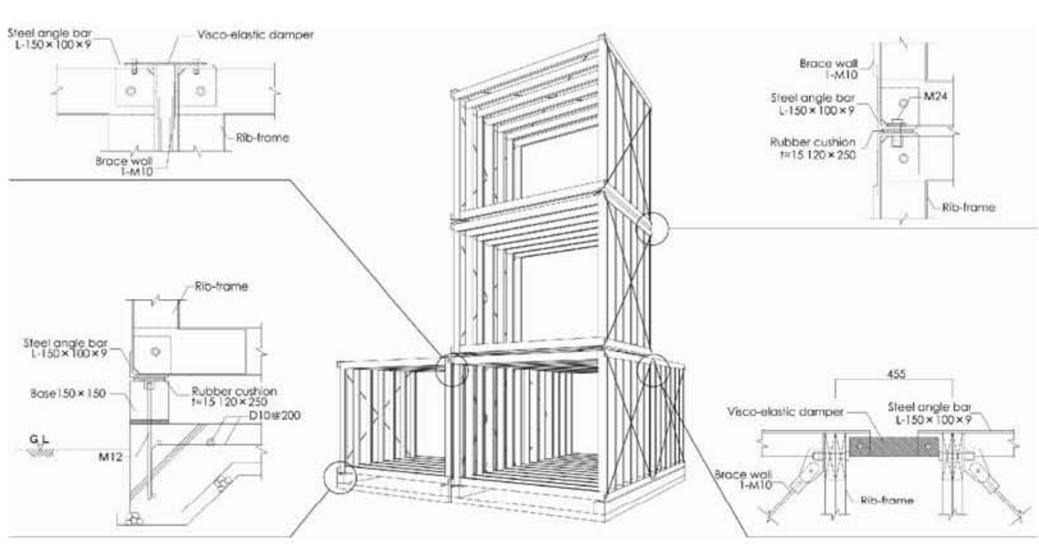

Fig. 7 Joint system of units

locking or collecting basic units together, the j.Pod design becomes applicable to some cellular-type buildings such as housing, apartment buildings and hotels. It can also be applied to larger spaces that require larger-scale constructions: in this case, the unit's dimensions must be developed with a longer span (Katagihara, Masuda et al. 2005; Katagihara, Barr et al. 2005).

Unit module

The j.Pod unit has standard internal dimensions of 3,640mm width x 2,730mm height x 2,730mm depth, occupying $10m^2$. The unit's major components are timber rib-frames arranged in a 455mm pitch, steel angle bars joining the corner of each rib-frame and structural plywood panels or steel cross-bracings placed to each surface.

The unit's scale is determined in accordance with the following criteria:

1. The unit area of $10m^2$ corresponds with the general size of a 6-tatami mat room, considered in Japan to be the adequate minimum scale for living space.
2. Each internal dimension of the unit follows the standard module of a structural plywood panel. A standard size is 910mm x 1,820mm, and many other building materials are also standardized in accordance with this module.
3. The 455mm pitch rib-frames can be used not only for the construction of the main structure, but also as intermediate posts providing a base for interior carpentry work. Whereas conventional building methods usually require intermediate posts to be put in once the construction of the main structure is finished, the short interval between rib-frames makes them suitable for the direct attachment of wall panels, etc. This can contribute to the simplification and shortening of the construction process.
4. All the parts can be hand-carried by one or two workers, as shown in Table 2.
5. Most raw timber is sold in lengths of 3m or 4m. At this length, they can be logged easily in the mountains and transported by truck. It is also the size most commonly required for conventional timber frame structures. The modules used in the j.Pod unit are 2,910mm and 3,820mm in length. This puts them within the length range by which timber is marketed in Japan for its most effective use.
6. The external dimensions of the unit are kept within the standards set by the Road Traffic Law in Japan for four-ton trucks, which

Components	Weight (kg)
Lumber 1	8.5
Lumber 2	11.1
Plywood panel	12.9
Steel angle bar	51.0

Table 2 Weight of major components

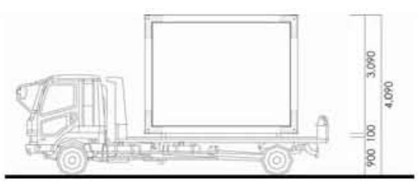

Fig. 8 Transportability of rib-frames

carry the unit's pre-fabricated rib-frames. The height of the truckload conforms to the 22nd article of the Road Traffic Law (below 4.1m) (Figure 8).

7. Roofing and other optional parts, such as utility units, can be flexibly fixed because of the construction-friendly advantages of timber, which enables the use of screws and nails to detach and replace materials. Moreover, some part of rib-frames can be cut out in order to make the required openings within the bounds of structural safety.

Timber Material

The use of home-grown timber is essential to the j.Pod concept. At present, a surplus of Japanese cedar is grown in much of the country. By incorporating the use of structural timber, the j.Pod's design supports the development of a more sustainable timber industry in Japan in the following ways:

1. **Application of unused timber**

Figure 9 shows the typical lumber pattern of a 35-45 year old Japanese cedar (about 30cm in diameter), grown extensively in Japan. The center part of the felled tree is usually cut to square lumber to meet the demand for the columns and beams used in conventional timber frames. However, there is less of a demand for the excess wood that surrounds the part that is cut to board lumber, mainly because various industrial or imported products are available as substitutes for board lumber. Instead, board lumber is used for the purpose of finishing materials, furniture and fixtures, scaffold planking and many other processed products. The j.Pod unit uses sections of Japanese cedar board lumber cut to the 36 x 180 mm j.Pod standard in the case of a two-story building. In this way, it uses the non-core or surrounding parts of the timber that are currently under used.

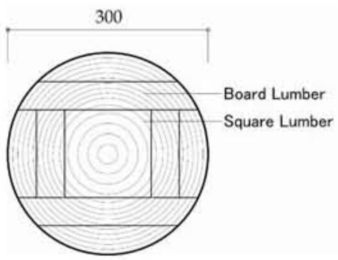

Fig. 9 Typical lumber pattern

2. **Application of defective timber**

As forest management has downgraded in response to the decline of the timber industry, poor management has produced sub-standard timber with a low market value. In addition, the market value for timber with worm track or black coloration is also low; most timber showing either of these defects is shredded for wood pulp.

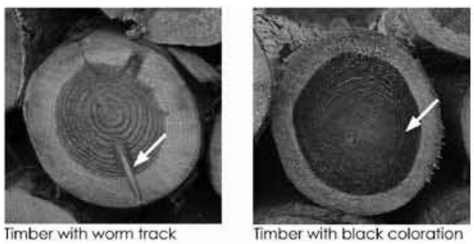

Fig. 10 Blemished appearance of Japanese cedar

Structurally, wood of this quality is strong enough to use and is regarded as defective only on account of its blemished appearance (Figure 10). The j.Pod unit makes positive use of these timbers, having first checked their performance by strength tests.

3. **Application of timber with low strength**

Japanese cedar is not generally as strong as Japanese cypress, another popular timber material in Japan (Figure 11) (Forest Technology Division of Hyogo Pref. Technology Center for Agriculture, Forestry and Fisheries 2005). Longitudinal elasticity is proportional to material strength. Conventional design criteria that set requirements for the material strength of existing construction methods (see the Design Criteria and Instruction of Wood-based Structure 2002) currently determine that only about 60 per cent of all cedar timber is appropriate for use in construction. Yet the use of the dynamic analysis method to evaluate structural safety on the base of strength tests (Figure 12, Kuwajima and Kamada 2005) has proved that the j.Pod unit can use more Japanese cedar safely. According to test results for a rib-frame constructed from 36 x 180mm j.Pod standard cut-sections of Japanese cedar, approximately 80 per cent of all the cedar can be used for a two-story building. The percentage increases to about 90 per cent for a one-storied building (Figure 11). The strength of Japanese cedar is influenced by the climate in which the tree grows, the areas where it is planted and the species with which it co-exists. The dynamic analysis method maximizes the performance of distinctive regional materials and accumulates data on each material for appropriate application.

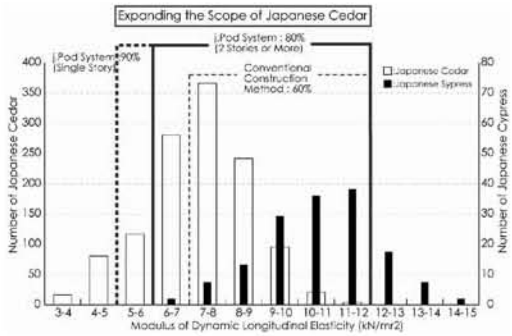

Fig. 11 Frequency table of lumber strength (Japanese cedar and cypress)

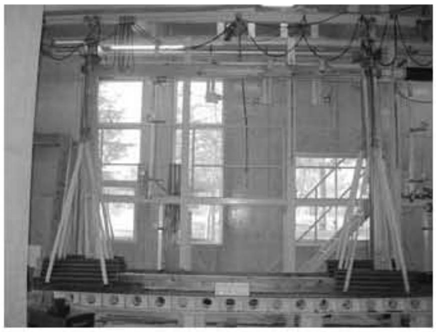

Fig. 12 Strength test of a rib-frame

Manufacturing of rib-frame and unit assembly

The rib-frame consists of pairs of lumber, joined to neighboring lumber by sandwiched L-shaped steel plates that are nailed together using an ordinary nail gun (Figure 13). The kind of complicated pre-cut curving of beam-column joints used in conventional timber frame structures is not necessary to joint together the parts of a j.Pod. This simple process means a rib-frame can be manufactured in most local fabrication plants. In fact, rib-frames must be prefabricated in a factory so the strength of the structurally important corner joints can be tested more easily. The *in-situ* assembly process of binding rib-frames into units is done easily, mostly by craning and bolting, allowing for easy construction and dismantlement. The unit's simple construction means safety can also be tested effectively.

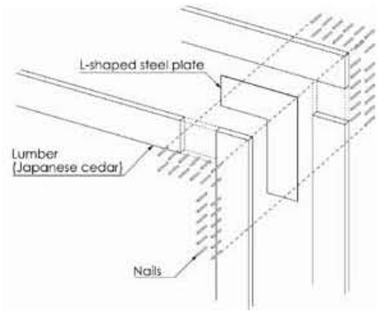

Fig. 13 Joint detail of a rib-frame

These simple methods mean that the j.Pod unit can be assembled with ease by unskilled laborers working in any local workshop or factory. The use of local timber reduces the need for transportation and the speed at which a unit can be constructed – the process is much faster than conventional building methods – means that cheaper construction costs raise the cost performance of the j.Pod unit compared with other building methods.

4. Practical applications: aiming at alternative architecture

4.1 Architecture trials

Two trial architectures were constructed in November 2004 after the basic performance and details of the units' assembly were confirmed using a full-scale structural model (Figure 14). Their outlines are as follows (Figure 15).


Fig. 14 Full-scale structural model

Trial architecture 01
Construction site: north campus of Kyoto University, Kyoto, Japan
Building use: seminar rooms
Floor area: 40.76m^2
Units: three units (one unit with cross-bracings and two units with structural plywood panels)
Duration of build: 2–31 March 2005

Trial architecture 02
Construction site: Field Research Center of Kyoto University, Wakayama, Japan
Building use: educational and research rooms
Floor area: 77.79m^2
Units: six units (three units with structural plywood panels for the first story and three units with cross-bracings for the second story)
Duration of build: 1 March–5 April 2005

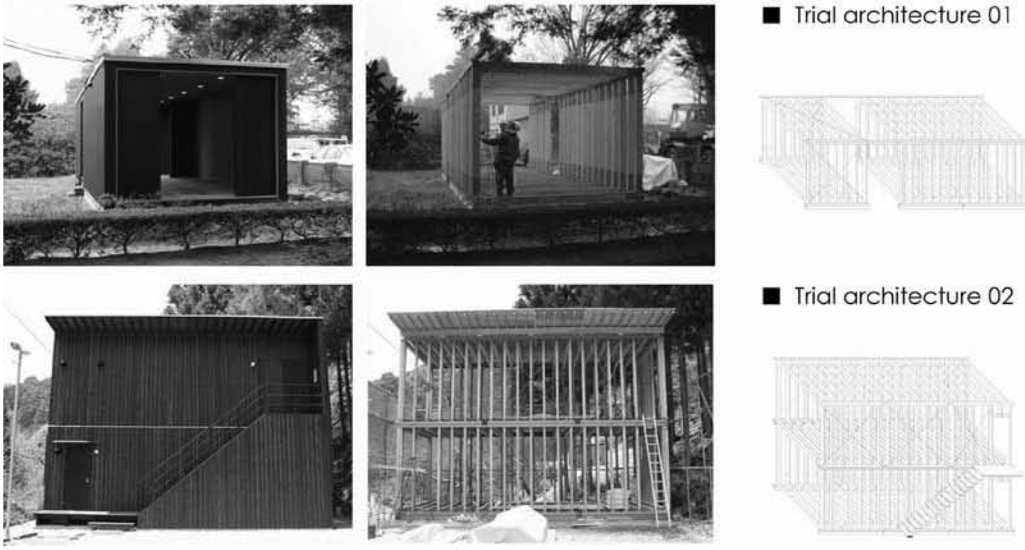

Fig. 15 Two architecture trials

Unit assembly

Figure 16 shows the construction process of the first trial architecture. Manufactured rib-frames for three units were transported to the site by a four-ton truck. Four workers (1 crane manipulator, 1 crane operator, and 2 assembly workers) started to assemble the units after concrete foundations had been laid. The process of the units' assembly took about 3 hours (1 unit per hour). However, interviews with the workers indicated that the completion process would decrease to about 40 minutes per unit once the workers were accustomed to assembling j.Pods. In the case of the second trial architecture, the process was almost the same but the three units for the second floor were craned up after being assembled on the ground to reduce the construction time.

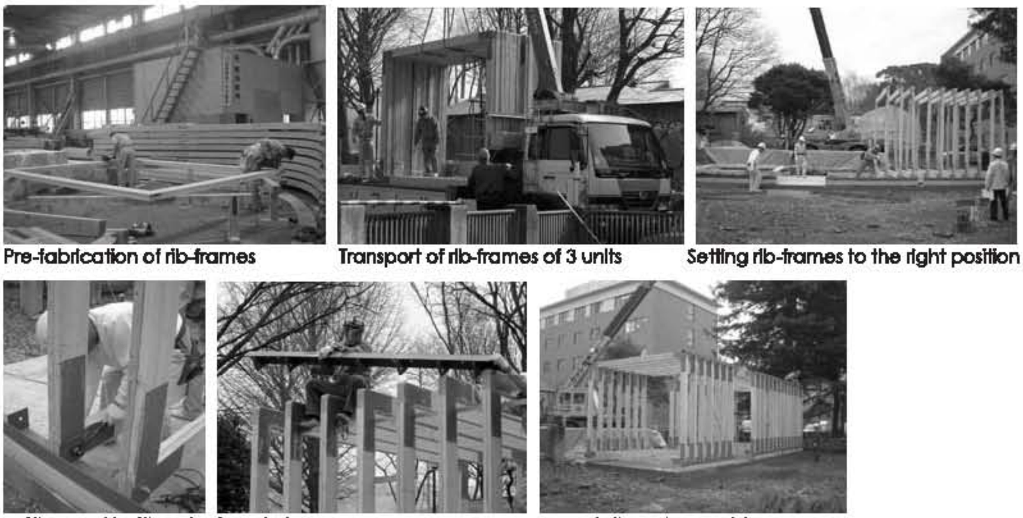

Fig. 16 Construction process of the first architecture trial

These two trials confirmed the effectiveness of pre-fabrication and assembly *in-situ*. The process of bolting the joints together made it easy to practise quality control (Kobayashi, Shiogai et al. 2005).

4.2 Basic combinations of units

The characteristic structural independence of the j.Pod units makes it possible to combine them in various patterns for practical use. The units' combination should fit more complicated conditions than those demanded by trials in order to meet the needs of building types, functional requirements, the specific contexts of a site and the arrangement of electric, air-conditioning, and sanitary facilities. Five feasible patterns of basic combinations (Figure 17) make the j-Pod applicable to a variety of practical projects:

1. "Tube" can create a required living space by linking units normally.
2. "Gap" can create the space for a staircase or a void room between units.
3. "Slide" can create a portion for an opening by displacing a unit.
4. "Skeleton" can create an open-air space such as a balcony, by using a framing unit.
5. "Rotation" can give an opening in any direction by rotating a unit.

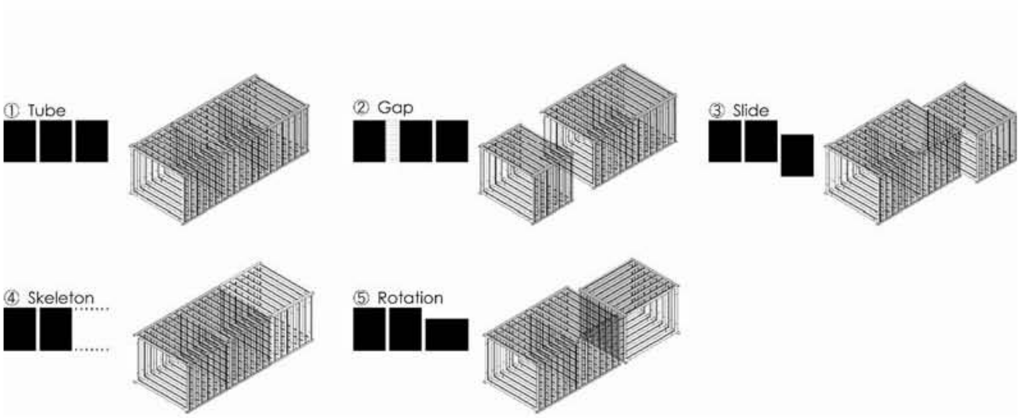

Fig. 17 Basic unit combinations

4.3 Application for practical use

Two practical projects have been ongoing since December 2005: the first, a private house, and the second, a block of prefectural apartments (see Figures 18 and 19). These projects aim to gauge the practical use of j-Pod units by confirming their assembly and construction processes, the processing cycle of local timber materials, etc. In short, the projects test the concept of the j.Pod unit.

Private housing project
Construction site: Kagoshima-city, Kagoshima prefecture, Japan
Building use: private family use
Floor area: 123.49m^2
Units: eight units plus four units of one-third depth (all units with structural plywood panels)

The composition of units makes a space for a stairwell and an entrance hall by following the basic "gap" combination. The units open south to allow in as much daylight as possible. Because the private house is located in an irregular-shaped site, each block of units divided by the hall staircase is displaced to fit to the site's shape. Extra units of one-third depth are placed to adjust the required space and create balconies.

Prefectural apartments project
Construction site: Yumesaki town, Himeji city, Hyogo, Japan
Building use: prefectural apartments (20 dwelling units)
Floor area: approximately 1,400m^2
Units: 88 units plus 36 units of one-third depth for balconies (all units with cross-bracings)

Although four types of dwelling units are required, each type offers the same utilities in terms of a bathroom and a lavatory room. Positioning the bathroom in the gap eliminates the difference in floor level. At the same time, it ensures enough longitudinal space for the piping of water sully and drainage. The number of units and the size of the gap can be adjusted to create the different types of living area required. This project also uses extra units of one-third depth for balconies adjoining the full opening direction of the units.

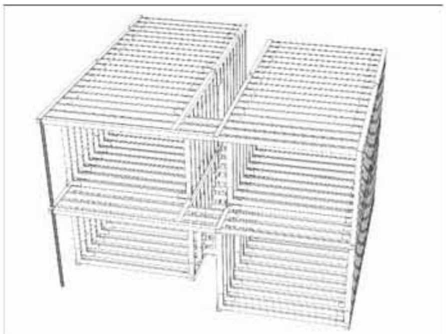
Fig. 18 Frame structure of private housing project

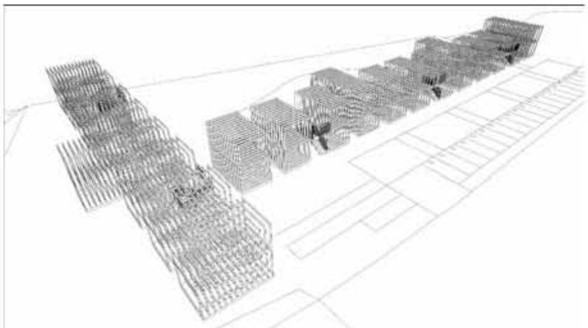
Fig. 19 Frame structure of prefectural apartments project

Conclusion

The j.Pod unit is a sustainable building system that has the potential to promote domestic timber use. The system's developers hope its effective use will foster new local networks of builders, users and timber resources that should generate an alternative wooden culture across Japan. The j.Pod's local focus offers one response to the global environmental issues we all face today. While some model projects are emerging, several hurdles must be overcome – and the system's cost and energy efficiency determined – before the concept will win widespread public acceptance.

Acknowledgements

We would like to express our appreciation to associates of the j.Pod team: Mr. Kenichi Katagihara, Ms. Yoko Masuda, Mr. Kazuyoshi Takagi, and Mr. John C.A. Barr. We also thank assisting students Mr. Morio Kito, Ms. Kaori Inoue and Mr. Tomō Sato. Final thanks are given to Prof. Masaru Tanaka and Prof. Noriyuki Takeuchi of Kyoto University for their warm support to the j.Pod unit.

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